Aerosol-Cloud-Drizzle-Turbulence Interactions in Boundary layer Clouds

Bruce Albrecht
University of Miami
Rosenstiel School of Marine and Atmospheric Sciences
4600 Rickenbacker Causeway
Miami, FL 33149-1031

Award Number: N000140810465

LONG-TERM GOALS

The long term-goal of this project is to provide an improved description and understanding of the effects of aerosol-cloud interactions and drizzle and entrainment processes in boundary layer clouds for the purpose of developing, improving, and evaluating cloud and boundary layer representations in LES, mesoscale and large-scale forecast models.

OBJECTIVES

The scientific objectives are to: 1) document the structure and characteristics of entrainment circulations in marine stratocumulus and fair-weather-cumuli, 2) characterize the vertical distribution of drizzle and how it relates to cloud and mesoscale circulations; 3) investigate the relative role of cloud thickness, cloud turbulence intensity, and aerosols on precipitation production; 4) study the processing of aerosols by cloud processes; and 5) explore mass, moisture, and aerosol transports across interfacial regions at cloud base and at the capping inversion.

APPROACH

The observations needed for this study are made using the NAVY CIRPAS Twin Otter research aircraft and includes the use of an FMCW cloud radar to track drizzle and cloud features while making simultaneous *in situ* measurements of aerosols and cloud characteristics. Further, we use the cloud radar with radar chaff to track air motions in and out of the clouds. Cloud seeding techniques demonstrated in an earlier ONR funded study are extended to study the response of cloud and drizzle processes to the artificial introduction of CCN and giant nuclei under differing aerosol backgrounds. In addition, a set of aerosol and cloud observations in trade wind cumulus clouds using the CIRPAS aircraft with the cloud radar was designed and carried out. The observational components of this study are made in environments where a strong-aerosol-cloud variability was observed. This included observations made during VOCALS (VAMOS Ocean Cloud Atmosphere Land Study) Regional Experiment off the coast of Chile (Oct.-Nov. 2008) where satellite observations indicate strong gradients in cloud properties off the coast. Further from the South Florida area of fair-weather cumulus clouds (Jan. 2008) where clouds with both marine and continental characteristics were observed. This was followed by a set of observations made in 2010 of cumulus clouds in off of Barbados. These studies included the participation of a number of graduate students and a technician/data analyst. For

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Aerosol-Cloud-Drizzle-Turbulence Interactions in Boundary layer Clouds**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Miami,Rosenstiel School of Marine and Atmoshperic Science,4600 Rickenbacker Causeway,MIami,FL,33149**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the VOCALS study we collaborated with Dr. Carl Friehe and Djmal Khief (U. Calif. Irvine) on turbulence observations from the Twin Otter and with Dr. Patrick Chaung (U. Calif. Santa Cruz) on cloud physics measurements. Dr. Haflidi Jonsson, the chief scientist for the CIRPAS Twin Otter (TO), has been an integral collaborator in all projects involving this research aircraft.

WORK COMPLETED

From 15 October to Januray-February 2008, the CIPAS Twin Otter was used to study aersosl, cloud, precipitation and turbulence observation in the South Florida area. A total of 15 flights were flown and provided sampling over a wide range of aerosol, cloud and boundary layer conditions. Flights were made over water and over land to provide boundary layer turbulence variations. Substantial boundary layer variations were observed and cloud conditions encountered included nearly solid stratocumulus, shallow non-precipitating cumulus, and shallow precipitating cumulus. Thus a full range of aerosol, cloud, and boundary layer conditions were sampled during the deployment and a rich data set for understaing key physical processes operating in these clouds was obtained. Work is currently in progress to analyze the data that were collected during these aircraft missions and will be compared with the observations made over the open ocean east of the island of Barbados from 15 March to 15 April 2010. During these studies 4 University of Miami gaduate students (one funded by this grant) participated in the aircraft observations. Further, undegradaute meterolgy students from UM toured the Twin Otter facility and received instument tutorials as an enhancement to their meterological intrumentation class during the time the aircraft was in Miami.

As part of this research project the CIRPAS Twin Otter (TO) research aircraft was deployed for VAMOS Ocean-Cloud-Atmosphere-Land Study -Regional Experiment (VOCALS-REx) that was undertaken from October to November 2008 over the subtropical southeastern Pacific to investigate physical and chemical processes important for boundary layer and cloud processes in this region. The CIRPAS Twin Otter aircraft made 19 research flights off the coast of Northern Chile during VOCALS-REx from Oct. 15 to Nov. 15. Cloud conditions were excellent during this deployment. The flight strategy involved operations at a fixed point (20 S; 72 W; reference point alpha) that allowed for a definition of the temporal evolution of boundary layer structures, aerosols, and cloud properties. Each flight included 3 to 4 soundings and near-surface, below-cloud, cloud base, in cloud, cloud top, and above inversion observations along fixed-height legs. This study used the aerosol, cloud, boundary-layer thermodynamics and turbulence data from those 18 flights to investigate the boundary layer, and aerosol-cloud-drizzle variations in this region.

The Barbados Aerosol Cloud Experiment (BACEX) was planned by our research group and then carried out from 15 March to 15 April 2010. The purpose of this field experiment was to observe the time evolution of the cloud and precipitation characteristics of individual oceanic cumulus clouds and to develop statistics on aerosol, cloud, and precipitation under varying aerosol conditions. The principal observing platform for the experiment was the CIRPAS TO that was equipped with aerosol, cloud, and precipitation probes and standard meteorological instrumentation for observing mean and turbulent thermodynamic and wind structures. The highlight of the TO observing package was an upward facing FMCW Doppler 95 GHz radar (designed and fabricated by ProSensing). The use of the FMCW radar, which has a dead zone of less than 50 m, allows for radar observation in close proximity to the *in situ* probe measurements. The Doppler spectra from the radar proved to be rich in structure that will help deconvolve the contributions to the radar returns from both cloud and rain. The aircraft was used to characterize the structure of shallow to moderately deep (cloud tops less than 2 km) and mostly precipitating marine cumulus clouds. A total of 15 aircraft flights were made just upstream

from a point on the eastern shore of Barbados (Ragged Point) where surface aerosol measurements (Joe Prospero, University of Miami) were made along with aerosol characterizations from a NASA AERONET tracking sun photometer for aerosol optical depth (AOD) and a micro-pulse LIDAR. Routine rawindsonde observations made daily from the island (by Barbados Meteorological Service) and observations from an S-Band radar (by Caribbean Meteorological Organization) on Barbados were collected in support of BACEX.

Cloud radar observations from the CIRPAS Twin Otter were made in support of the TO operations made off the coast of California during July-August 2011 in support of The Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 that was led by Dr. Lynn Russell and with collaborators John Seinfeld and Armin Sorooshian. The observations from the FMCW radar that was operated by our group are being used to document the cloud structure observed on the flights flown during E-PEACE. A set of experiments where giant (salt) nuclei where intentionally dispersed in solid stratocumulus clouds off the coast was executed. The giant nuclei released during these experiments were milled salt particles (about 3 μm) that were coated to prevent sticking. They were dispersed using a mechanism that auger fed particles into fluidized bed of grit before emitting them to the outside in a pressurized flow. After the particles were dispersed flights were made in the cloud at lower levels where the radar and the in situ probes sampled the air mass that was seeded with the salt particles to see how the cloud and precipitation characteristics of the cloud were modified.

RESULTS

The observations made during the VOCALS deployment provide a unique characterization of the cloud and aerosol variability in the coastal environment. The marine atmospheric boundary layer structures observed showed relatively little variability and indicated little influence from meso-scale and large-scale systems. The boundary layer structures observed on several of the VOCALS flights were remarkably similar, although the observed aerosol concentrations in the boundary layer and the cloud water content and the liquid water path of the clouds topping the boundary layer varied considerably. On 10 of the flight days, the boundary layer was well mixed, the clouds sampled were non-precipitating, and conditions at the top and the bottom of the mixed layer were very similar. Calculated boundary layer back trajectories for the 72 hours prior to the observations at 20^oN and 72^oW remained mostly over coastal ocean areas and indicate that advective effects were generally small during this time. Thus the boundary layer, cloud and aerosol structures sampled on the individual days were likely to be steady and close to equilibrium. Despite the constancy of the thermodynamic structures of the boundary layers studied on these 10 flights, the subcloud CCN varied substantially and was closely coupled to the cloud droplet concentrations as well. CCN in the boundary layer for these cases ranged from 180-580 cm^{-3} in the relatively thin capping clouds. The liquid water path in these clouds ranged from 22 to 73 gm^{-2} and was positively correlated with the aerosol and cloud droplet concentrations (Fig. 1) as described in a GRL paper (Zheng et al., 2010). Processes that may link the aerosol concentrations and the liquid water path and explain the observed positive correlation are currently under study using satellite observations along low-level trajectories and LES to study the effects of aerosols.

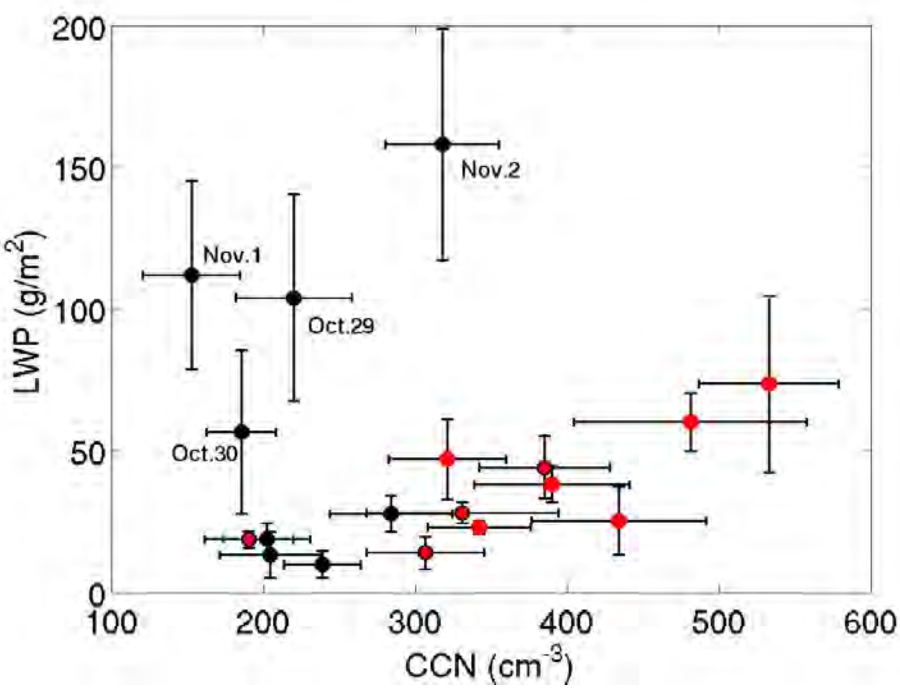

Figure 1 . LWP as a function of sub-cloud CCN concentrations for all flights during VOCALS at Point Alpha. The error bars through these symbols indicate the standard deviation of CCN and estimates of LWP uncertainty.

During BACEX the Twin Otter was able to sample many cumulus clouds in various phases of growth during BACEX and under different aerosol loading. Precipitation varied from light to heavy with the convection showing substantial meso-scale organization on several of the flights. Rapidly dissipating clouds (life-times of less than 10-15 minutes) were probed on several occasions by cloud penetrations starting from cloud top and working downward with time. The time evolution of these strongly precipitating clouds and the relative role of precipitation and evaporation (through entrainment) in explaining these results are under study. The principal variability in the background aerosols observed during these flights was associated with African dust above the boundary layer. On two days when convection was completely suppressed, an African dust event associated with record Aerosol Optical Depths (AODs) for Barbados during this time of the year was observed. The vertical structure of the aerosols and the boundary layer observed during these cases will be documented. The thermodynamic structure and the aerosol structure associated with one of these cases are shown in Figs. 2 and 3. The thermodynamic profiles show a clear layered structure with the SAL layer capping the marine boundary layer. Aerosols in the near-surface mixed layer are relatively mixed with height as are the aerosols in the SAL. The intermediate layer (between the SAL and the surface mixed layer) shows substantial variability in the thermodynamic and the aerosol structures. This variability is most likely linked to convective processing of the aerosol sometime in the history of the intermediate air mass as it moved across the Atlantic. This unique data set is being used to further study aerosol transports and processing during this major African dust event.

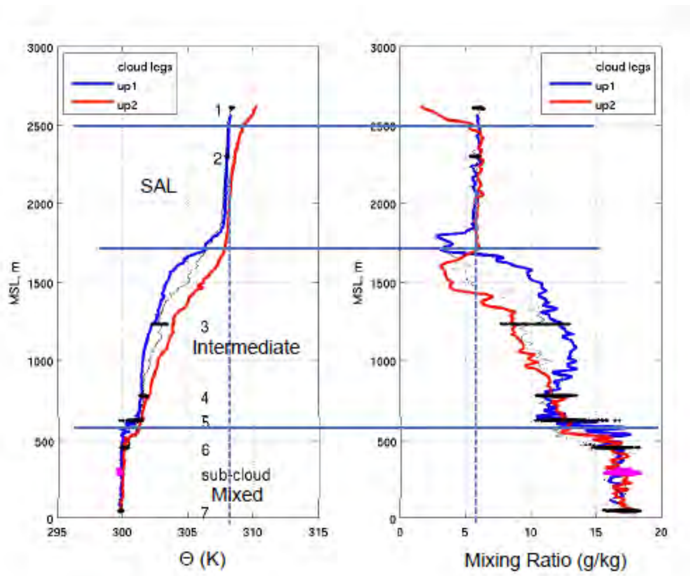

Figure 2. Potential temperature (θ) and mixing ratio profiles obtained on soundings during BACEX on 1 April during an intense African dust event. The Saharan Air Layer (SAL) is observed above the marine boundary layer. The intermediate layer extends from this layer to the top of the sub-cloud mixed layer. The black data points were obtained on ~10 minute legs flown at a constant altitude and show the spread of θ and mixing ratio at these levels. The dashed lines are extrapolation of the SAL values to the surface.

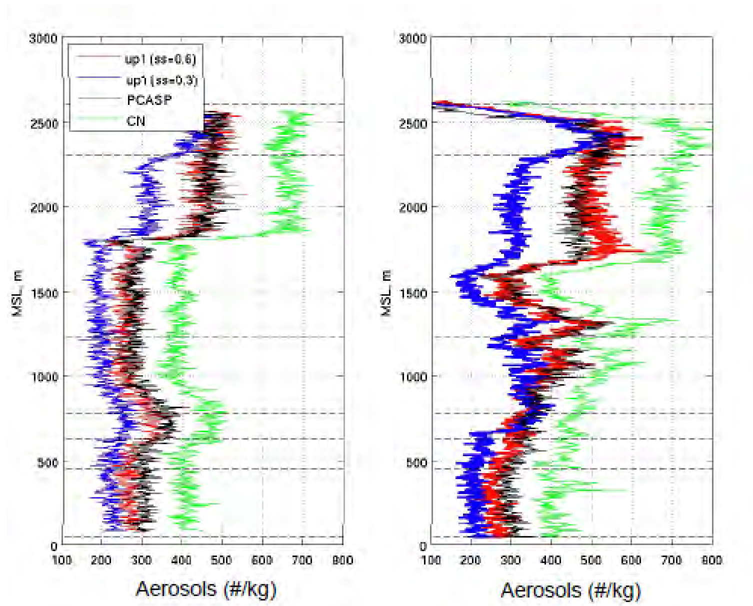

Figure 3. Aerosol concentrations (# per unit mass of dry air) from PCASP (0.1 to 3 µm), CCN (at 0.3 and 0.6 super-saturations), and CN from TO observations. The left and right panels are for two profiles made in the same vicinity but separated by about 2 hours.

Two new techniques for using an airborne cloud radar for probing air motions in precipitating clouds and tracking circulation in the clear air around and beneath the cloud were demonstrated during BACEX. The first is based on a technique that allows for the retrieval of vertical air motion from an airborne W-Band radar using Mie scattering thumbprints in the radar Doppler spectrum. In cases where raindrops have diameters comparable to the wavelength (3.2 mm) of the 95-GHz radar, Mie scattering explains the oscillation of the backscattering cross section between successive peaks and valleys as a function of the raindrop diameter (Pavlos et al., 2003). The minimum in the Doppler spectrum can then be used to determine the air vertical velocity. At radar wavelengths of 3 mm, the first minimum in the backscattering cross section occurs at a raindrop diameter equal to 1.65 mm. Despite the relatively shallow nature of the convection observed on the BACEX flights (tops at 1.5-2 km), raindrops exceeding this diameter were observed on several occasions and allowed us to make a first-ever successful test of this technique from an aircraft. This work was submitted to the *J. Appl. Meteor. and Climate*.

The second technique demonstrated was the use of radar chaff to track motions associated with entrainment and detrainment processes at the top and edges of cumulus clouds the airborne FMCW 95 GHz Doppler radar on the Twin Otter. The chaff used for this experiment was pre-cut metallic coated fibers (cut to 1/4 of the wavelength of the radar) that were dispersed from canisters carried in a pod beneath the wing of the CIRPAS Twin Otter. The fibers have a terminal velocity of about 2 cm/s and follow air motions. The chaff experiments were designed to examine entrainment-detrainment processes and the subsiding shells observed around small cumulus clouds. After the chaff was dispensed near cloud top, the aircraft made penetrations of the cloud at lower levels to observe the chaff clouds above with the radar. Examples of the radar returns from radar chaff above the aircraft flight level are shown in Figs. 4 g and d. In this case chaff was released in a downdraft along the edge of the cloud (Fig. 4a). Here the environmental air above the cloud top descended to the level of equilibrium potential temperature, along the downshear side of out-cloud edges through a downdraft and was subsequently entrained laterally into the cloud at the the lower observational level. This study also provides a more complete picture of the in-cloud flow patterns that have been hypothesized in previous studies and is the first-ever use of a cloud radar to track radar chaff flows in and around cumulus clouds.

IMPACT/APPLICATIONS

The results from these studies are intended to provide an improved understanding of the physical processes associated with cloud-aerosol-drizzle-turbulence interaction that will lead the way to improved representation of the processes in models operating over a wide range of scale and particularly for mesoscale and large-scale forecast models used in coastal and marine environments. The successful completion of the VOCALS Twin Otter observational period has already produced results that show a positive correlation in the CCN concentration in the boundary layer with the observed LWP. The variations are substantial and the reasons for these changes are under study. The aircraft observations that were obtained during VOCALS have been used for evaluation of the COAMPS real-time forecast (Wang et al., 2011).

The air velocity (Mie minimum) retrieval technique that was demonstrated from the BACEX observations has important implications for future observational studies. Using a downward looking cloud radar (95 GHz) one could, for example, retrieve the updraft and downdraft structures in tropical cyclone rainbands in radar sampling volumes extending from the aircraft to the ocean surface. A radar designed to operate at a shorter wavelength (e.g. 1 mm) could be used for retrieving air motion

associated with smaller raindrops. The demonstration of the use of radar chaff optimally cut for use with a cloud radar provide a unique observational technique for understanding the flows in and around boundary layer clouds and sets the way for future observational studies using this technique. If scanning cloud radars with differential polarization capabilities were used, the returns from cloud and chaff could be separated.

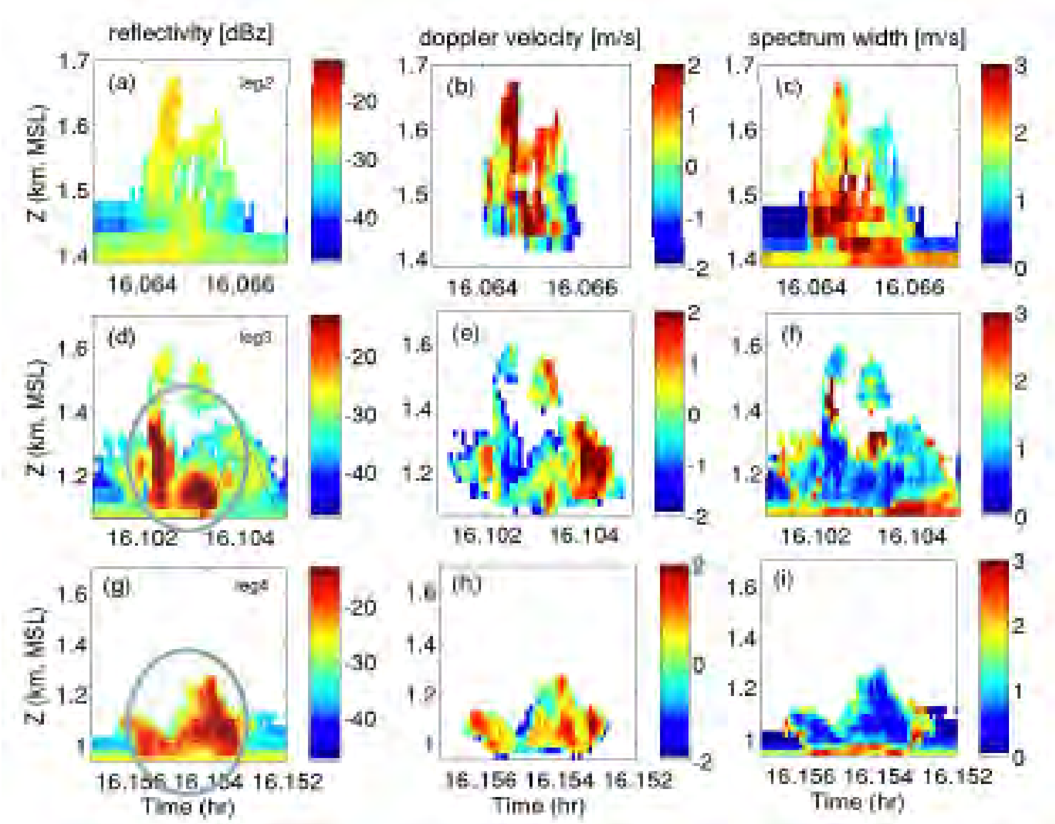

Figure 4: Time-height cross sections of (a, d, g) zeroth moment (power/reflectivity), (b, e, h) first moment (vertical velocity) and (c, f, i) second moment (spectrum width) of Doppler spectrum for the chaffed cloud on 29 March 2010 through leg 2 to leg 4 (top-down). The aircraft observations were made at an air speed of about 60 m $s^{-1}$and thus cloud widths are approximately 430 to 860 m. Liquid water contents were added as black solid line in panle d. Note that reversed time axes are used for the chaffed cloud at leg 4 (panles g-i) to give a spatial consistency for penetrations made in opposite direction. .

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